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Extended summary

Innovative methods and advanced digital technologies to support product design in collaborative environments

Curriculum: Mechanical Engineering and Engineering Management

Author

Margherita Peruzzini

Tutor

Ferruccio Mandorli

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Abstract. In industrial design different knowledge, competences and expertise need to be shared among design experts and different viewpoints need to be integrated in order to achieve the main design objective: designing an innovative and successful product. Nowadays boundaries are no longer limited to the single company but comprehend numerous partners and act worldwide according to the concept of the extended enterprise (EE). As a consequence, design assumes a highly collaborative and dislocated character (co-design) and collaboration becomes crucial to realize high quality products and services. Different types of digital technologies and ICT tools can be adopted to support the design process by improving communication within the design team, facilitating interaction with different product representations, reproducing traditional face-to-face activities also in remote modalities, and efficiently sharing data along the whole product development. However, available technologies are not widely used because selection is a crucial task and the correlation with the achieved-achievable benefits is difficult to define.

This thesis falls in such a scenario and deals with innovative methods and tools for collaborative design. In particular, it analyses collaboration from multiple viewpoints by considering both human factors and system performances, and proposes a structured methodology to assess the quality of co-design processes in multidisciplinary and distributed teams. Such a method is applied to different contexts for technological benchmarking, to define the most proper tools able to support a specific use, and for system evaluation, to assess the collaboration quality in mediated processes. The proposed method has been applied to numerous industrial cases and the most significant examples are described. Experimental studies allow highlighting the main limits of actual applications and defining a new interaction paradigm able to represent the EE needs and novel guidelines for innovative collaborative environments.

Keywords. Collaborative Product Design (CPD), Computer Supported Cooperative Work in Design (CSCWD), Human-Computer Interaction (HCI), Virtual Reality (VR).

1 Problem statement and objectives

Collaborative design environments represent a fairly recent concept that had quickly spread in product design. They basically refer to a new way of performing traditional design activities by adopting physical or virtual spaces where people collaboratively work together on physical or virtual models as product representations. Nowadays such environments are necessary to satisfy modern markets needs and produce complex and high quality products, which imply multidisciplinary actions. These characteristics directly derive from the new scenario of extended enterprise (EE) [1], which makes the design context geographically distributed, particularly heterogeneous and strongly dynamic. As a result, complicated interactions among multidisciplinary design teams including cooperation, coordination, and communication are necessary [2]. During collaborative design team members should explore their own knowledge and expertise and integrate different views to achieve the final common objective: the new product to be designed [3].
Team working is highly multi-functional and inter-company: collaboration among people and integration of knowledge, data, processes and practices become inevitable [4]. When the design team is distributed, virtual collaborative environments are necessary to connect people and knowledge. Design reviews (DRs) are the most critical moments during the whole product development. During DRs specialists of different disciplines actually work together on the same product data to monitor specific design aspects at time, focus on specific issues, find feasible solutions, share information and knowledge and finally assess different alternatives. As team members usually have different abilities, different priorities in their own work and conflicting viewpoints about product attributes, collaboration is not a trivial task [5].
Such a scenario triggers research toward the development of new methods and tools for managing collaborative virtual teamwork. In order to realize successful co-design, direct observation suggests that three main aspects should be optimized: how design team members work together and interact each others, how product representations are perceived during design reviews by each member of the design team, and how supporting tools affect team collaboration and product perception during multidisciplinary reviews. They respectively refer to three main areas: human-human, human-product and human-computer interaction. Numerous methods and tools for managing design activities in distributed teamwork have been defined in recent years to improve collaboration. However, they are not diffused nor usefully exploited in industry, especially when Small and Medium enterprises (SMEs) are involved in large networks of companies. Main problems concern the tools selection and the evaluation of potential benefits [6].

The present research work aims at finding a synthesis among all collaborative issues by investigating design collaboration, studying the application of supporting technologies in industrial design and defining advanced co-design tools able to improve collaboration and realize effective collaborative environments.
The research goals can be summed up into three main points:

- Definition of effective collaborative environments according to the specific context of use, in order to properly sustain both people communication and knowledge management in respect of the collaboration requirements;

- Quantification of the achieved benefits in collaborative process activities by measurable parameters;
- Elaboration of a new strategic approach to design collaboration and definition of a roadmap for future developments in co-design.

2 Research planning and activities

The research program consists of three main parts: 1) investigation of human interactions and cognitive actions during DRs and analysis of technology mediation, 2) definition of a goal-oriented methodology to achieve the research goals, 3) experimental application of the proposed method to different design context and analysis of the obtained results.

Firstly, human interactions during DR activities are analysed by considering the relationships among human beings (human-human), between humans and product representations (human-product) and between humans and technology (human-computer). Human-human interaction is investigated by considering the cognitive models of human communication [7,8] and the main promoting factors within the design team [9,10]. Human-product interaction considers the human perception theories [11] to define how individuals perceive products. Human-computer interaction considers the theories of mediated communication and the main affecting factors [7,12] to understand how human-human and human-product interactions are affected by the technological support. A general framework to describe such an influence is drawn (Fig.1).

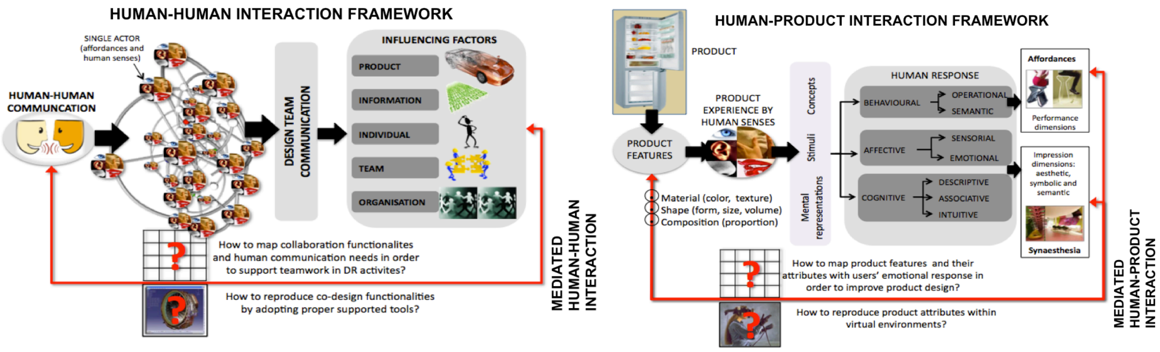

Figure 1. Conceptual frameworks representing mediated interaction in product design

The research is then taken the field by analyzing an industrial inter-companies network, the CO-ENV Consortium (www.coenv.it). It has been closely investigated to comprehend how companies actually collaborate in real projects and which aspects characterize human interaction by different points of view. By means of the performed analysis, traditional collaboration patterns are replaced by a network-based interaction mode. Furthermore, different forms of collaboration have been recognized depending on the design tasks (conceptual design collaboration, advanced design collaboration, interplay collaboration) and the time-space domain (synchronous, asynchronous, co-located, remote). For each of them, the main collaborative issues have been described.

The core of this PhD research is the proposed methodology. It allows to analyze collaborative processes for different purposes and to assess human collaboration in various scenarios. It can be adopted for benchmarking different technologies as well as evaluating performance of specific applications and comparing the quality in use. It can be defined goal-oriented as it has a fixed structure and application procedure but it can be adapted by different situations on the basis of the specific goal. Furthermore, it exploits QFD and HoQ [13] to progressively correlate the main significant aspects considered (collaboration forms or dimensions, evaluation heuristics and metrics, co-design functionalities, project tasks, objective and subjective experimental data from users, etc.) and quantify them by adopting interrelated matrices. Methodology can be summed up into six steps (Fig.2).

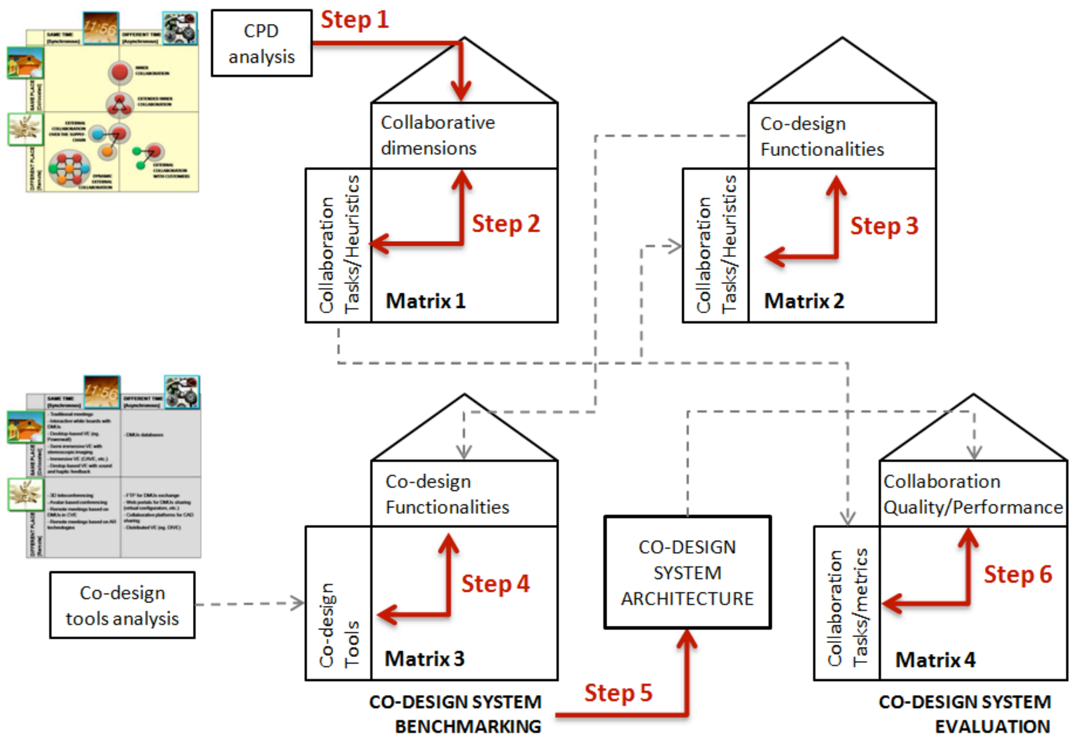

Figure 2. The QFD-based method's overview for benchmarking and testing co-design tools and evaluating design collaboration

The methodology has then applied to the three forms of interaction considered: human-human, human-product and human-computer interaction. In each case, final purposes are different so method application also differs in the selected tasks, heuristics, evaluation metrics, benchmarking weights, design activities under investigation, etc. As a consequence, three classes of metrics are defined for each case:

a. Heuristics/metrics of design collaboration able to assess collaborative design quality (human-human). They are full described in a research work [5];
b. Heuristics/metrics of product impression able to investigate the quality of product perception during collaborative DRs (human-product). They are described in few research works [14,15];
c. Tasks/metrics of team collaboration able to assess collaborative teamwork quality (human-computer). Measurement approach and metrics are described in few research works [6,16].

The main experimental applications refer to the following topics:

1. Definition of a complex collaborative platform for supporting co-design within the CO-ENV Consortium. This study aims at defining the most proper system architecture according to the CO-ENV requirements and evaluating the teamwork performances in manufacturing EE. Final goal has been achieved by applying both benchmarking and evaluation protocol and heuristics/metrics of team collaboration. About testing modalities, experts from University and Industry have been involved for benchmarking and all the CO-ENV Consortium companies for experimentation. Results consisted of: identification of a set of suitable co-design modules (1) [6], system implementation (2) [17,18] and evaluation of performance in use/quality of team collaboration (3) [16].

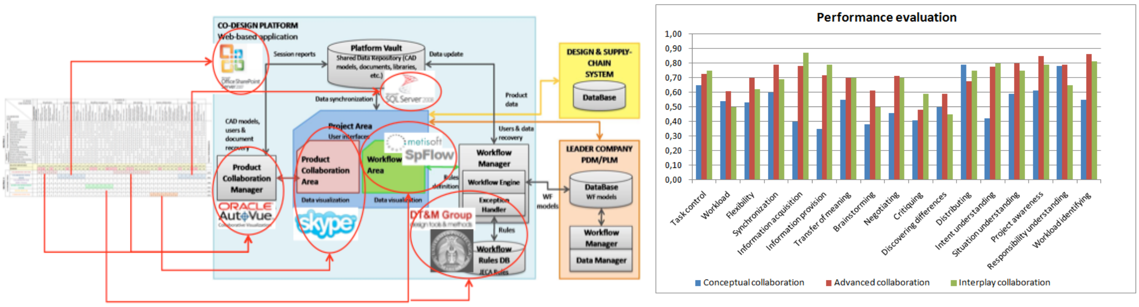

Figure 3. The CO-ENV co-design platform: definition of the system architecture (on the left) and team working evaluation on real co-design projects (on the right).

2. Investigation of human collaboration in design reviews. In particular, two studies have been developed to analyse team working in both co-located and remote meetings. They are based on the application of heuristics/metrics of design collaboration, the direct observation of users at work and monitoring by Diary Study and Interaction Analysis. Concerning the analysis of remote DRs, three different systems have been compared in different contexts of use and collaboration quality objectified [19,120]. About co-located DRs, traditional and VR-based environments have been tested in order to compare collaborative design practice by objective indicators [5].

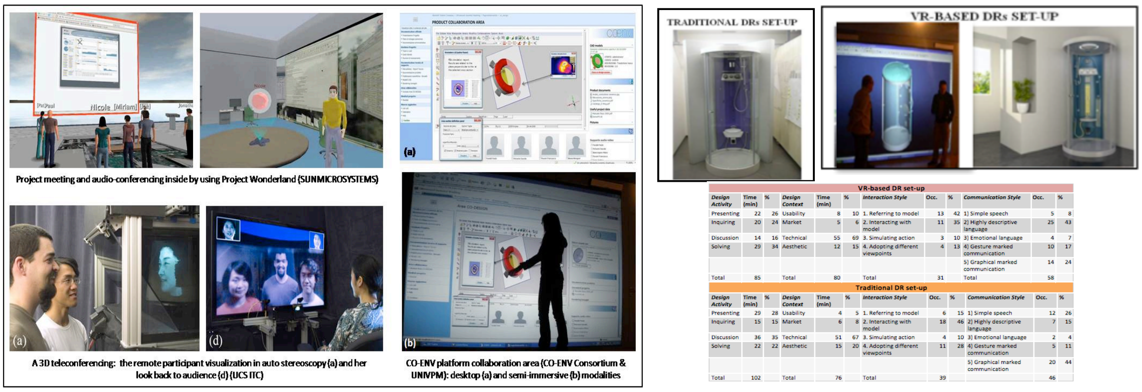

Figure 4. Examples of co-design environments' experimentation during remote (on the left) and co-located (on the right) design reviews

3. Evaluation of human-product interaction during DRs. In this context two different studies have been developed: the former concerns with the analysis of product perception during DRs by adopting different prototyping techniques (traditional, VR-based and sample-based); the latter is focused on usability tests by adopting different

prototypes of interactive interfaces (RP-based, VR-based, MR-based and SW simulation). The first one has been realized in house-hold appliaces field in collaboration with Indesit Company [14], while the second one interested wellness products, in particular remote controls and has been realized in collaboration with Teuco Guzzini [21]. In both cases results refer to: the assessment of the protocol metrics and the definition of their degree of relevance, the identification of the best perceived design solutions, the assessment of product usability assessment within different prototyping environments and the comparison between the performance obtained, the correlation between metrics and product properties.

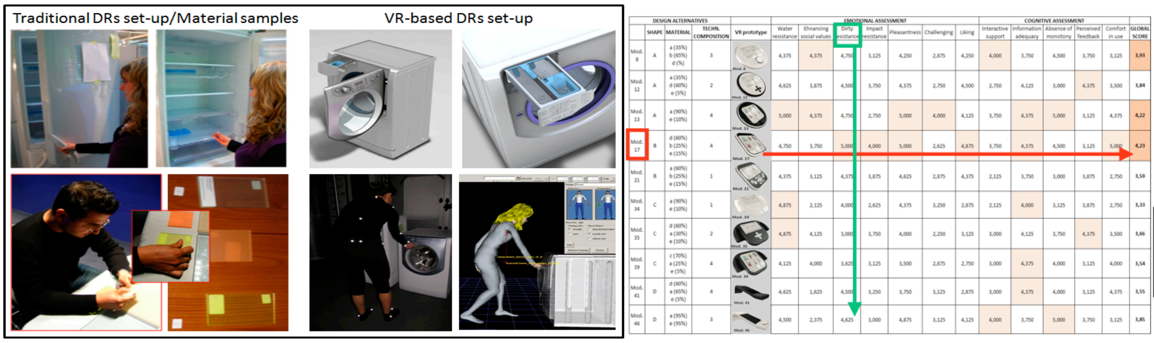

Figure 5. Comparison of different prototyping set-ups (on the left) and product usability assessment according to the proposed protocol (on the right)

For each case study, the specific experimental protocol, the experimental modalities, the adopted investigation techniques, the elaboration of testing results and the final results discussion are detailed in the PhD thesis.

3 Analysis and discussion of main results

The research activity ended with the critical discussion of the experimentation's findings and the definition of a new paradigm of interaction to enhance collaborative design. On the basis of the actual limitations, the author defines a strategic roadmap for future applications and a list of functional requirements for developing an innovative supporting tool and achieving ideal collaboration. In particular, the new system idea is based on a novel model of human interaction, the open-chain collaboration, an original knowledge structure, based on the cobweb model, and a new approach to product knowledge representation, based of the exchanging nodes as places of interaction (Fig.6). The new system concept aims at overcoming the limits of actual models and tools and paving the way to innovative collaborative environments.

This thesis includes an innovative method for supporting the definition and the validation of collaborative environments for product design and an original framework to address future developments. The main original contributions can be sum up as follows:

- use of cognitive models of communication to investigate both human-human interactions and product perception and design experience;
- adoption of cognitive and human-oriented viewpoint in the analysis of design review process and human interaction mechanisms, instead of traditional functional and process-oriented analysis;

- combination of teamwork analysis with emotional and cognitive aspects in the protocol metrics definition. It allows to better analyze collaboration by overcoming traditional approaches that are mainly focused on performance;
- application of QFD and House of Quality techniques for investigating and especially objectifying design collaboration;
- definition of a new mode of interaction for inter-company collaboration based on open-chain collaboration and an innovative cobweb model to conceptualize a future system architecture. The first upsets the concept of industrial chains in virtue of an open and agile collaboration style, the latter renews traditional network-based models, proposes a novel way to organize the design knowledge in multi-company environments and introduce additional co-design functionalities.

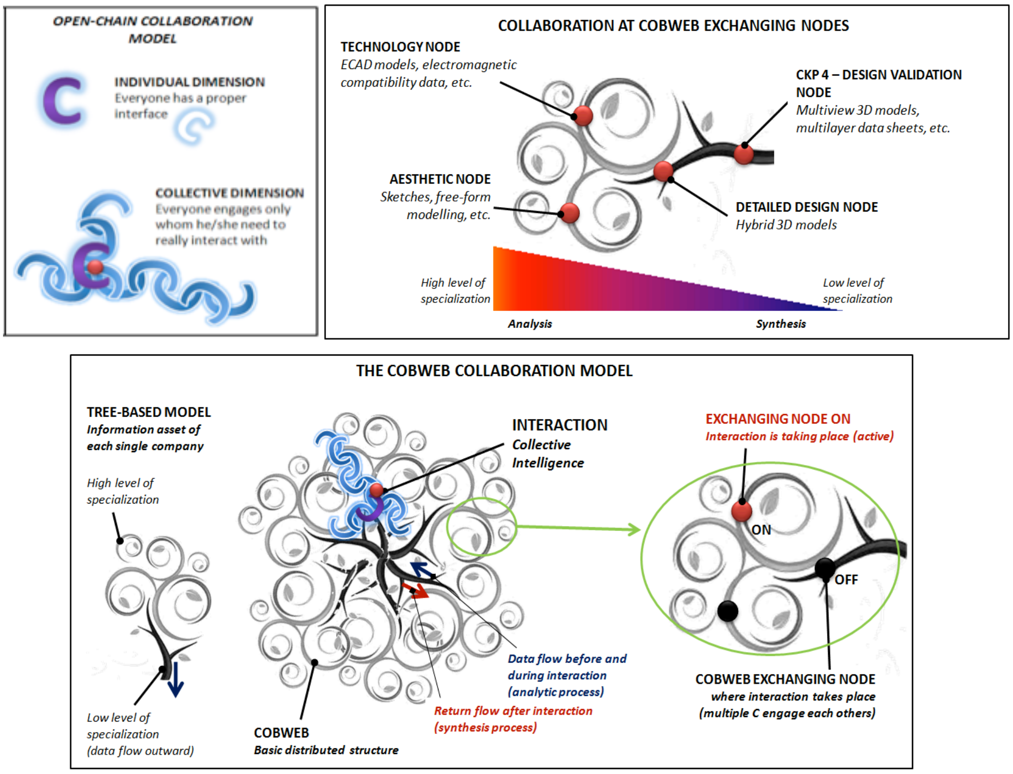

Figure 6. The new model of interaction proposed for supporting co-design

4 Conclusions

The PhD research work faces design collaboration in industrial product design from multiple perspectives: it deals with numerous and complex issues, it focuses on different aspects of design communication and it investigates several and various real applications in practice. The activity was intense and pursy, and concluding is not easy.

Despite the variety of tools available to perform cooperative work and share product data, it can be concluded that design collaboration is still not fully supported. Furthermore, tools' selection and customization are crucial activities in order to use performing and profitable technologies and effectively generate high quality products in respect of time and cost constraints. In order to support extended enterprises and design teamwork, the author defined and applied a novel methodology to fill the gap between available co-design technologies and successful applications. Collaboration is analyzed by focusing not only on performance, but also on cognitive aspects, human factors and interaction issues. As a result, an innovative interaction paradigm to represent design collaboration is defined to guide future research developments.

This thesis presents some interesting novelties concerning the approach used in analyzing design communication and human relationships, the concept of a goal-oriented methodology that can be customized for different application depending on the specific scopes, and the modelling of human interactions during co-design activities.

References

[1] Byrne, J.A., Brandt, R., and Port, O., (1993). The virtual corporation. The company of the Future will be ultimate in adaptability, Business Week, pp.36-40.

[2] Shen, W., Norrie, J.P., and Ma, Y.S., (2000). Multi-Agent Systems for Concurrent Intelligent Design and Manufacturing, Taylor & Francis, London, UK.

[3] Kleinsmann, M., (2006). Understanding collaborative design, Delft University of Technology, Delft.

[4] Pol, G., Merlo, C., Legardeur, J. and Jared G., (2007). Collaboration in product design and PLM-based coordination, Proceeding of International Conference on Product Lifecycle Management 2007, Stezzano, Italy, 11-13 July.

[5] Mengoni, M., Peruzzini, M. and Germani, M., (2009a). The Impact of Virtual Environments on Humans Collaboration in Product Design, Proc. International Conference on Engineering Design (ICED'09), Norell Bergendahl M. et al., Eds, Stanford University, Stanford, CA, 24 - 27 August. ISBN 978-1-904670-16-2.

[6] Germani, M., Mengoni, M. and Peruzzini, M., (2009b). A method to define a co-design platform to support cooperative work in SMEs, Proc. International Conference on Product Lifecycle Management PLM09, Bath, United Kingdom, 6-8 July. CD-ROM, ISBN 978-1-86197-173-1.

[7] Norman, D.A., (1988). The Design of Everyday Things, MIT Press.

[8] Noble, D. and Letsky, M., (2002). Cognitive-Based Metrics to Evaluate Collaboration Effectiveness, Proceedings of the RTO SAS symposium on Analysis of Military Effectiveness of Future C2 Concepts and Systems, Den Hague, The Netherlands.

[9] Nardi, B., (2005). Beyond Bandwidth: Dimension of Connection in Interpersonal Communication. Proc. of CSCW 2005, Vol. 4, pp. 91-129, DOI 10.1007/s10606-004-8127-9.

[10] Maier, A.J., Eckert, C.M. and Clarkson, P.J, (2009). Towards managing team interfaces: an elicitation of factors influencing communication, Proceedings of the International Conference on Engineering Design ICED09, 24-27 August, Stanford, CA, USA.

[11] Crilly, N., Moultrie, J. and Clarkson, P.J., (2004). Seeing things: consumer response to the visual domain in product design, Design Studies, Vol. 25, pp. 547-577.

[12] Whittaker, S., (2003). Theories and Models in Mediated Communication. In: Graesser, A. (ed.) The Handbook of Discourse Processes. Lawrence Erlbaum, Cambridge.

[13] Akao, Y. (1994). Development History of Quality Function Deployment, The Customer Driven Approach to Quality Planning and Deployment. Minato-ku, Tokyo 107 Japan: Asian Productivity Organization, 339. ISBN 92-833-1121-3.

[14] Mengoni, M. and Peruzzini, M., (2010). Usability Assessment to Address Interaction Design, Research in Interactive Design, Vol. 3, Springer Verlag (in printing).

[15] Mengoni, M., Peruzzini, M. and Germani, M., (2009b). Virtual vs Physical: an experimental study to improve shape perception, Proc. of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2009, San Diego, CA, USA, 30 August – 2 September. Vol. 2. ISBN 978-0-7918-4899-9.

[16] Germani, M., Mengoni, M. and Peruzzini, M., (2010b). Performance evaluation of co-design tools for extended enterprise, Proc. of the International Conference on Product Lifecycle Management PLM10, Bremen (Germany), 12-14 July. ISBN 987-3-9812025-3-3.
[17] Mengoni, M., Germani, M., Peruzzini, M. and Mandolini, M., (2010a). A novel knowledge-based approach to support virtual teamwork in collaborative design, Proc. 9th International Conference on Tools and Methods of Competitive Engineering TMCE 2010, Ancona, Italy, 12-16 April, Vol. 1, pp: 461-474. ISBN 978-90-5155-060-3.
[18] Mengoni, M., Graziosi, S., Mandolini, M., Peruzzini, M., (2010d). A knowledge-based workflow to dynamically manage human interaction in extended enterprise, International Journal on Interactive Design and Manufacturing (IJIDeM), Springer, published on line October 2010 (DOI : 10.1007/s12008-010-0103-7).
[19] Germani, M., Mengoni, M. and Peruzzini, M., (2010a). A benchmarking method to investigate co-design virtual environments for enhancing industrial collaboration, Proc. World Conference on Innovative VR 2010, WINVR2010, Ames, IOWA (USA), 12-14 May 2010. ISBN 978-0-7918-3869-3.
[20] Germani, M., Mengoni, M. and Peruzzini, M., (2010c). Method for Evaluating VR-based tools for Collaborative Design, in J. Pokojski et al. (eds.), New World Situation: New Direction in Concurrent Engineering, Springer-Verlag London Limited. ISBN 978-0-85729-023-6. DOI: 10.1007/978-0-85729-024-3_44.
[21] Mengoni, M. and Peruzzini, M., (2010). Usability Assessment to Address Interaction Design, Research in Interactive Design, Vol. 3, Springer Verlag (in printing).